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Innovative Water Management Using Advanced Irrigation Systems and Biochar

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INNOVATIVE WATER MANAGEMENT USING ADVANCED IRRIGATION SYSTEMS AND BIOCHAR

by

Jonathan A. Holt

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of the requirements for the degree

of

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in

Plant Science

Approved:

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ABSTRACT

Innovative Water Management Using Advanced Irrigation

Systems and Biochar

by

Jonathan A. Holt, Master of Science

Utah State University, 2021

Major Professor: Dr. Matt Yost
Department: Plant Soils and Climate

Two approaches to water optimization in agriculture are to increase soil water retention and improve the efficiency of irrigation. A soil amendment that has received attention for its ability to increase soil water retention is biochar. Two studies were conducted to evaluate how wood biochar influences the productivity, crop quality, and soil water tension of irrigated alfalfa (Medicago Sativa L.), corn (Zea mays L.), and wheat (Triticum L.). One study evaluated a biochar rate of 22 Mg ha^{-1} at two irrigation levels (full vs. partial), where soil-incorporated biochar increased silage corn yield by 12% in 2018 and reduced yield by 10% in 2019. Top-dressed biochar had no impact on alfalfa yield from 2018-2020. The other trial had six to seven biochar rates (0 – 67 Mg ha^{-1}), and a 22 Mg ha^{-1} wood chip rate at one site. This trial displayed a yield decrease of 0.01 Mg ha^{-1} of wheat grain for each Mg ha^{-1} of biochar applied, however there were no impacts on silage corn production. Data obtained over ten site years showed minimal impacts from biochar on crop yield, quality, or soil water tension, leading us to conclude that wood biochar was not an effective tool for enhancing crop production or conserving irrigation water in arid agriculture.

Most pivot sprinkler packages in the Intermountain West are mid-elevation sprinkler application (MESA). Studies of low elevation spray application (LESA), low energy precision application (LEPA), and mobile drip irrigation (MDI) have demonstrated greater efficiency than MESA but have rarely been tested at a reduced application rate. Eight site-years of data were collected at four Utah farms from 2018 to 2020, to evaluate crop yield and quality responses to full and reduced rates of each system in alfalfa, silage corn, and small grains. Data showed that the advanced systems sometimes maintained yield and quality while applying 15 to 25% less water, but not consistently. This led us to conclude that there is not one system that will have the best results all the time, but that tailoring the package to the field characteristics is where optimization with these packages can occur.

(66 pages)

PUBLIC ABSTRACT

Innovative Water Management Using Advanced Irrigation

Systems and Biochar

Jonathan A. Holt

Two approaches to water optimization in agriculture are to increase soil water retention and improve the efficiency of irrigation. A soil amendment that has received attention for its ability to increase soil water retention is biochar, the remaining biomass after high C materials have been pyrolyzed (burned with limited oxygen and heat). Two studies were conducted at a total of 10 site-years in Utah from 2018 to 2020 to evaluate how wood biochar influences the productivity and crop quality of irrigated alfalfa (Medicago Sativa L.), corn (Zea mays L.), and wheat (Triticum L.), along with soil water tension. One study included a single biochar rate of 22 Mg ha^{-1} at two irrigation levels (full vs. partial), where soil-incorporated biochar increased silage corn yield by 12% in 2018 and reduced yield by 10% in 2019. Top-dressed biochar had no impact on alfalfa yield from 2018-2020, in either irrigation rate. The other trial had six to seven biochar rates (0 – 67 Mg ha^{-1}), plus the addition of wood chips at a single rate (22 Mg ha^{-1}) at one site. This trial displayed a yield decrease of 0.01 Mg ha^{-1} of wheat grain for each additional Mg ha^{-1} of biochar applied, however there were no impacts on silage corn production. Data obtained over ten site years showed minimal impacts from biochar on crop yield, quality, or soil water tension, leading us to conclude that wood biochar was not an effective tool for enhancing crop production or conserving irrigation water in arid agriculture.

Most pivot sprinkler package in the Intermountain West are classified as mid-elevation sprinkler application (MESA). Several studies of low elevation spray application (LESA), low energy precision application (LEPA), and mobile drip irrigation (MDI) have demonstrated greater efficiency than MESA, due to less loss between the time that the irrigation water leaves the nozzle and enters the rootzone. However, these advanced sprinkler packages have rarely been tested at a reduced application rate. Eight site-years of data were collected at four Utah farms from 2018 to 2020, to evaluate crop yield and quality responses to full and reduced rates of each system in alfalfa, corn, and small grains. Soil water tension was also measured. Data showed that the advanced systems were sometimes able to maintain yield and quality while applying 15 to 25% less water, yet there were situations where MESA outperformed the advanced systems. This led us to conclude that there is not one style that will have the best results all the time, but that tailoring the package to the field characteristics is where the optimization with these packages can occur. Therefore, this chapter is being published as an Extension Guidebook for farmers.

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CHAPTER I

BIOCHAR HAD MINOR IMPACTS ON YIELD, QUALITY, AND WATER AVAILABILITY OF ALFALFA, CORN, AND WHEAT

1.1 | INTRODUCTION

Agriculture consumes more than 78% of the diverted water in Utah (Dieter et al., 2017), while irrigated acres represent just over 2% of the total area (Allen, 2017). This water supports an annual $400 million crop industry in the state that contributes $335 million in cash receipts from milk production and helps feed nearly 340 thousand head of cattle annually (USDA-NASS, 2016). In the United States, about 28% of harvested cropland is irrigated, but those hectares produce an equivalent value of crops as the other 72% of the land that is not irrigated (USDA, 2019). Since the 1960s, global irrigated land has increased by 117%, and now encompasses about 20% of all cultivated land (FAO, 2011). The increase in production from irrigation has been one of the key factors in decreasing the average amount of land required for food production per person. Having an increased ability to ensure crop water demands are met can boost production levels without additional land in some areas. For instance, in the United States a 65-year study found yield increases from 25% in winter wheat and 270% in corn, with the addition of irrigation (Kukal & Irmak, 2019). Despite the important role irrigation plays in feeding the global population, there are increasing instances of water reallocation from agriculture to urban regions (Garrick et al., 2019). Some areas that have historically been dependent on ground water for irrigation are finding that unsustainable withdrawals have resulted in a depleting source that requires action to preserve (Scott, 2019). These challenges will likely increase as additional water shortages and weather extremes due to climate change are anticipated (Vogel et al., 2019). Due to these and other mounting concerns, water optimization in agriculture is a high priority.

Several agricultural water optimization options exist, this paper will explore one option in particular: improving soil water retention. One potential method for improving agricultural water optimization is increasing soil water retention by amending soils with organic materials. Biochar is a charcoal product formed from heating a high C material in an environment with limited O, thus retaining much of the C biomass. This process is referred to as pyrolysis. The materials converted to biochar differ around the world, usually depending on what low value, high C material is in abundance. Forest deadfall and waste wood from industry are abundant and will eventually require disposal, and biochar production and field application could be a responsible way to restore soil C (McCollum, 2011). For example, in Utah, pinyon pine (*Pinus edulis* Engelm.) and juniper (*Juniperus* osteosperma (Torr.) Little) woodland areas have overgrown, doubling the fuel load in some places, and overtaking valuable sagebrush ecosystems (Tausch & Hood, 2007). These often require clearing to restore habitats and prevent or control wildfires. Once clearing has occurred, the deadfall requires disposal, which is often handled by burning large piles. Though limited by scale, burning these waste materials in a kiln instead of in open piles, reduces air pollution, decreases the chances of wildfires, prevents damage to the soil, and produces high C biochar for use as a possible soil amendment (McAvoy & Dettenmaier, 2017). Other feedstocks used worldwide include, but are not limited to, rice (*Oryza sativa* L.) husk, bean straw (*Phaseolus* L.), saw dust, and corn stalks (Liu, Jiang, & Yu, 2015). Beyond the charcoal production, and depending on the production method, the pyrolysis process can also produce valuable oil, as well as gas that can fuel the pyrolysis process (Apostol, McAvoy, Rappold, & Kuhns, 2017).

The potential to convert waste materials into a soil amendment and other valuable products while sequestering C, has earned biochar considerable interest. Biochar has also been recognized as a soil amendment with potential to absorb and hold water, nutrients, hazardous and toxic elements, as well as increase soil C storage (Karhua, Mattila, Bergströma, & Regina, 2011; Uzoma, Inoue, Andry, Fujimaki, Zahoor, & Nishihara, 2011). For example, results from a study on oil and gas sites in the Uinta Basin, indicate that wood biochar can improve water holding capacity of Utah soils (Peltz & McAvoy, 2020). Further, research conducted in the eastern United States found that wood biochar could increase the water holding capacity of loamy sand soils by 1.7% for every 1% (by mass) of biochar added to the soil, up to 9%, and Wang, Li, Parikh, and Scow (2019) found that coarse-ground wood biochar could help coarse textured soils retain more water in extreme situations, though the benefits were not long term due to pore spaces filling with silt. Small improvements in soil water retention could be a major benefit in arid and semi-arid regions, such as Utah.

Crop yield is one of the strongest driving forces behind decisions made on the farm – including the purchasing of soil amendments. The impact of biochar of crop yields will greatly influence the ability of growers to finance and apply biochar amendments. In 2017, Utah State University tested biochar pyrolysis temperature and particle size effect on lettuce (*Lactuca sativa* L.) production in Kaysville, Utah (Hunter, Cardon, Olsen, Alston, & McAvoy). In this study, biochar reduced lettuce yield in five of six treatments, however the researchers noted that they observed hydrophobic qualities in the biochar. In wheat, research in Washington determined that biochar rates up to 22.4 Mg ha^{-1} increased root and shoot mass of wheat, however, grain yield was not measured (Bista, Ghimire, Machado, & Pritchett, 2019). Several studies exist where the addition of biochar has decreased crop yields (Novak, Sigua, Ducey, Watts, & Stone, 2019; Brantley, Savin, Brye, & Longer, 2015). Sorensen and Lamb (2016) evaluated the effect that biochar rate had on the yield and quality of cotton (*Gossypium hirsutum* L.), corn, and peanut (*Arachis hypogaea* L.) in Georgia, USA and found that biochar rates up to 134 Mg ha^{-1} had no positive or negative effects on yield or quality. A later study by Sorensen and Lamb (2018) focused on the economics of biochar and stated, "Biochar would not be added as a yield enhancement but possibly as an income/economic incentive for growers as a "carbon credit" to sequester carbon sponsored by the government, private, or commercial entities." In the Intermountain West, such economic incentives for biochar do not exist, and the current cost of wood biochar is near \$350 Mg^{-1}. With little confidence regarding yield impacts from the aforementioned range of results, biochar needs to be evaluated in the crops (alfalfa, corn, and wheat) that represent most of the cropland in the western United States. Possible soil water retention or crop production enhancements would lead to increased value and potential use of wood biochar as a soil amendment. It would also help improve tree thinning assessments by local and state agencies in this region. Thus, the objectives of this research were to: i) evaluate the impact of wood biochar rates on yield, crop quality, and soil water tension of corn and wheat production; and ii) determine the impact of a single rate of wood biochar on yield, crop quality, and soil water tension of alfalfa and corn production.

1.2 | MATERIALS AND METHODS

1.2.1 | Site characteristics

On-farm biochar trials were established in Cedar City, Elberta, and Mosida, Utah in the spring of 2018. That fall, an additional on-farm trial was established in Cornish, Utah. The first three sites were irrigated with center pivots, and the Cornish site with a lateral-move wheel line. Soil classification and textural group were obtained from the University of California-Davis SoilWeb (O'Geen, 2020; Table 1). All four sites had medium-textured soil ranging from loamy fine sand to silt loam. Soil pH, organic matter, P, and K concentrations were measured as the average of four composite samples, one per replication (15 cm deep × 1.9 cm i.d.) collected prior to study initiation (Table 1). The samples were analyzed at the Environmental Analytical Lab at Brigham Young University (Provo, UT, USA). Soil pH was determined on a saturated paste (Rhodes, J.D. 1982), organic matter by Walkley-Black dichromate oxidation (Walkley & Black, 1934), P concentrations by extraction with 0.5 M sodium bicarbonate (Olsen, Cole, Watanabe, & Dean, 1954), and K concentrations by extraction with 0.5 M sodium bicarbonate and analyzed by an AAnalyst 200 spectrometer (PerkinElmer, Waltham, MA; Schoenau & Karamonos, 1993). Weather data at all four sites were obtained from the Utah Climate Center (Logan, UT, USA) and were used to calculate cumulative precipitation and growing degree days for the growing season of each crop. Corn, wheat, and alfalfa growing degree days were calculated using base air temperatures of 10, 0, and 5°C, respectively. Measured cumulative precipitation and degree days were compared with their respective 30 yr. normals (1981-2010) provided by the National Oceanic and Atmospheric Administration (Silver Spring, MD, USA) (Fig. 1.1 to 1.6).

1.2.2 | Biochar and Irrigation Levels

An area of uniform topography was selected in each field to establish the biochar trials. Two separate trials were established, one with biochar rates and another with a single biochar rate at different irrigation levels. The Cornish and Mosida sites were the rate trials and evaluated an untreated control, along with 2, 6, 11, 22, and 34 Mg ha^{-1} rates of biochar, on 6 × 12 m plots. The biochar was top-dressed by hand once in the first year of the study, then incorporated by the cooperating grower's tillage practices at Cornish and Mosida. Biochar was applied in May 2018 shortly before spring tillage and corn planting at Mosida. Silage corn was also grown in 2019 and 2020 at this site with no repeated biochar application (Table 2). Biochar was applied in September 2018 before tillage and planting of soft white winter wheat at Cornish. Soft white winter wheat was also harvested at this site in the 2020 growing season. At Cornish only, an additional 67 Mg ha^{-1} biochar treatment was included, as well as a 22 Mg ha^{-1} treatment of unburned wood chips derived from local shipping pallets. The wood chip treatment was added to the evaluation because, similar to biochar, it can reduce waste and may sequester soil C, but without the costly pyrolysis process. At both of these rate trials, all treatments were arranged in a randomized complete block design with four replications of each treatment.

The Elberta and Cedar City sites were the irrigation level trials and evaluated a 22 Mg ha^{-1} biochar rate at full (100%) and partial (80%) irrigation levels (Table 2). This single biochar rate was assessed because it was the recommended rate for biochar application for field crops in neighboring states (Bista, Ghimire, Machado, & Pritchett 2019). The addition of the partial irrigation rate was to determine whether biochar could provide additional benefits to corn or alfalfa in a water-stressed environment. The full irrigation rate was produced using mid-elevation spray application sprinklers and the partial rate was irrigated with low-energy precision application sprinklers designed with nozzle reductions to apply 20% less water than the full irrigation treatment. Each irrigation level separately contained four replications of treated and untreated plots (6 × 12 m), arranged in a randomized complete block design. At the Elberta site, biochar was top-dressed applied by hand in May then incorporated into the soil with tillage prior to silage corn seeding. In Cedar City, the biochar was top-dressed on June 2018 to an established alfalfa crop, directly after the first harvest of the season was removed. For this reason, the biochar could not be incorporated at this site.

At all four sites, all crop management was performed by the cooperating growers who managed for maximum production levels. Tillage, planting, fertilizing, and pest management operations were conducted uniformly across the entire plot area. The corn at the Elberta and Mosida sites was fertilized with granular synthetic fertilizers and dairy slurry. Cedar City was fertilized annually with separate applications of livestock and hog manure composts, at 2.2 Mg ha^{-1}. In 2019, no N fertilizer was applied to the wheat at the Cornish site because it was first-year wheat following alfalfa and the alfalfa should have provided adequate N. However, P and K were applied based on soil tests results and Utah State University guidelines (Cardon, Kotuby-Amacher, Hole, & Koenig, 2008). In 2020, 135 kg N ha^{-1} as ammonium nitrate was broadcast in March.

The biochar used at all four sites was derived from wood and was obtained from the nearest manufacturer (Amaron Energy, Salt Lake City, UT, USA) in April 2018. The wood source was shipping pallets that were no longer suitable for commercial use. The pallets were chipped to 2 cm, and then pyrolyzed in a rotary kiln at 500°C. Four subsamples of the biochar (and wood chips at Cornish only) were collected and composited into a single sample for each site prior to application. Samples were analyzed at the Brigham Young University Environmental Analytical Lab (Provo, UT, USA) for P by 0.5 M sodium bicarbonate extraction (Olsen, Cole, Watanabe, Dean, 1954), K using 0.5 M sodium bicarbonate extraction (Schoenau & Karamonos, 1993) and AAS analysis (AAnalyst 200, PerkinElmer, Waltham, MA, USA), pH using a Thermo Orion Model 410A+ (Thermo Electron, Waltham, MA, USA), electrical conductivity using Rc-16C EC Conductivity Bridge (Beckman Instruments, Brea, CA, USA), and N and C using the combustion method (McGeegan & Naylor, 1988) in a Vario EL Cube (Elementar, Langenselbold, Germany) (Table 1.3).

1.2.3 | Soil Water Tension

Soil water tension was monitored at each site with solid-state electrical resistance sensors and Watermark 900m data loggers (Irrometer Company, Riverside, CA, USA). The Cedar City and Elberta sites had sensors in three replicates of the biochar treated and untreated plots of both irrigation treatment levels. In Mosida and Cornish, sensors were placed in three replications of the untreated control, and plots with 11 and 34 Mg ha^{-1} of biochar applied. At all sites, sensors were installed at 30 and 60 cm depths and water tension was measured every four hours throughout the growing season. At the three sites with annual crops (excluding Cedar City), sensors were removed prior to corn and wheat harvest and re-installed shortly after planting each year.

1.2.4 | Crop Yield and Quality

Alfalfa was harvested using a mechanical, walk behind sickle-bar mower. Harvests occurred about a day before the grower would harvest the entire field. The center 6 m^2 of each plot was harvested in 2018. This harvested area increased to 7.3 m^2 the following two years due to the use of a wider mower. The cutting height was set to the grower's usual cut height of 7.5 cm above the soil surface. All cut material was gathered and weighed. A subsample (about 200 g) was weighed in the field and dried with a forced air oven at 60°C until constant mass. The subsample was weighed then ground to pass through a 1 mm sieve using a Thomas Model 4 Wiley Mill (Thomas Scientific, Swedesboro, NJ, USA). Ground samples were analyzed by near-infrared reflectance spectroscopy (NIRS) using a FOSS DS2500 F (Foss North America Inc., Eden Prairie, MN) at the Utah State University Analytical Laboratories (Logan, UT, USA) using the 2020 legume hay NIRS consortium equations (NIRS Forage and Feed Consortium, Berea, KY) to estimate dry matter, ash, fat, crude protein (CP), acid detergent fiber

(ADF), neutral detergent fiber (NDF), and neutral detergent fiber digestibility 48 hr (NDFD). The following three quality parameters were calculated:

[Eq. 1] Total Digestible Nutrients (TDN) = (100 - (NDF - 2 + CP + 2.5 + Ash)) × 0.98 + CP × 0.93 + (Fat - 1) × 0.97 × 2.25 + (NDF - 2) × NDFD / 100 - 7

[Eq. 2] Relative Feed Value (RFV) = ((120 / NDF) × (88.9 - 0.779 × ADF)) / 1.29

[Eq. 3] Relative Feed Quality (RFQ) = (((0.012 × 1350 / (NDF / 100) + (NDFD - 45) × 0.374) / 1350 × 100) × TDN / 1.23.

Yield measurements were taken at each alfalfa cutting, except for the first cutting of 2018, as biochar treatments had not been applied. Total yield and average forage quality were calculated each year across all cuttings. This included three cuts in 2018, and four in 2019 and 2020.

Corn was hand harvested shortly before the grower's harvest, when corn was at approximately 650 g kg^{-1} moisture content. In each plot, plants were cut 15 cm above the soil surface in 3 m of the center two rows. All cut plants were weighed in the field, and a subsample of four plants from each plot were chipped in an Echo Bear Cat SC3206 Chipper Shredder (Crary Industries, West Fargo, ND, USA). Subsamples of chipped corn (~0.5 kg) were weighed then dried in a forced air oven at 60°C until constant mass. Dried samples were weighed, ground to pass through a 1 mm screen, and analyzed for forage quality using the same equipment and laboratory as alfalfa samples. In 2018 and 2019, grain measurements were taken by retaining an additional four plants from each plot. The ears were removed from the plants, and both were weighed and subsampled to be dried after the same manner. Once dried to constant mass, cobs were stripped of grain, and stover and grain samples were weighed to determine grain yield and harvest index. Due to a lack of response to the biochar, this measurement was not continued in 2020. The 2020 fermented silage corn NIRS consortium equations (NIRS Forage and Feed Consortium, Berea, KY) were used to estimate ash, CP, fat, NDF, NDFD, and starch and to calculate TDN:

[Eq. 4] $$TDN = 100 - (NDF - 2 + CP + fat + ash) \times 0.98 + CP \times 0.93 + (fat - 1) \times 0.97 \times 2.25 + (NDF - 2) \times NDFD / 100 - 7$$

Wheat was mechanically harvested using a plot combine (Massey Ferguson, Duluth, GA, USA) in a 16.3 m^2 area in the center of each plot. Grain samples were collected from the combine for each plot. In 2019, wheat test weight was measured using a Cox Funnel and density cup (Seedboro Equipment Company, Des Plaines, IL, USA). A subsample was dried in a forced air oven at 60°C until constant mass to determine dry matter yield. Another subsample was dried to <80 g kg^{-1} moisture content, ground through a 1 mm sieve, and analyzed for protein using the same NIRS instrument as corn and alfalfa. In 2020, access to equipment improved and CP, moisture, and test weight were all determined using an Inframatic 9500 Grain Analyzer (PerkinElmer, Akron, Ohio, USA) at the Utah State University Small Grains Research laboratory.

1.2.5 | Statistical Analysis

All statistical analyses were performed by site at $P \leq 0.05$ using the MIXED procedure of SAS (SAS Institute Incorporated, Cary, NC, USA). In all analyses, year was treated as a fixed effect and a repeated measure because the same plots were used each year. The first-order autoregressive covariance structure was used because it had the best fit among the several structures evaluated. Biochar rate was also considered a fixed effect with block and interactions including block as random at all locations. Dependent variables differed by site but included yield and various crop quality parameters. Data were analyzed separately by irrigation level at Elberta and Cedar City because the irrigation treatments could not be randomized and replicated due to logistical constraints of working with a center pivot. The UNIVARIATE procedure of SAS was used to inspect residuals to ensure that the assumptions of normality and equal variance were satisfied. All mean separations were conducted using Fisher's protected LSD at $\alpha = 0.05$. When the main effect or interactions involving biochar rate were significant, regression analysis was used to describe the response of the dependent variables to biochar rate. Several regression models were evaluated and the model that was significant at $P \leq 0.05$ and produced the smallest residuals that were normally and randomly distributed was selected (Kutner, Nachtsheim, & Neter, 2004).

1.3 | RESULTS AND DISCUSSION

1.3.1 | Biochar Rate Trials

1.3.1.1 | Wheat Grain

At the Cornish site in northern Utah, growing season (May – August) precipitation totals were 93 and 130 mm (Fig. 1.2) for 2019 and 2020 respectively (30 and 82% above the 30-year normal). Slightly cooler temperatures accompanied the increased precipitation as there was a 11% GDD decrease from the 30-year normal each season, at 2733 and 2745 (Fig. 1.1). The main effect of biochar rate influenced wheat yield, but the interaction of biochar and year was not significant (Table 1.4). Across years, biochar decreased wheat grain yield by 0.0100 Mg ha^{-1} for each 1 Mg ha^{-1} increase in the biochar rate (Fig. 1.7). Soil water tension was not considered as influential on yield, as the data did not display any periods of water stress. However, fertility came into question when a nitrogen-credit trial in the same field displayed a response to additional nitrogen, signifying a shortage of available N for maximum yield. Without excess N available, the biochar may have been in competition with the plants for N, as has been seen in other studies (Nguyen et al., 2017). When utilizing a biochar price of \$318 Mg^{-1} (cost of biochar in this study), application costs of \$8.81 Mg^{-1} (Sorensen & Lamb, 2018), at the recommended biochar rate of 22 Mg ha^{-1} (Bista et al., 2019), there is \$7190 ha^{-1} of fixed costs, even before adding any supplemental N, which may be required. At the current soft white wheat grain price of \$0.16 kg^{-1}, the yield losses at the 22 Mg ha^{-1} rate resulted in losses of \$33 and \$64 ha^{-1} (2019 and 2020). Therefore, not only would biochar need to be discounted or subsidized, but biochar application may also require substantial compensation for yield loss in some crops. Raw wood chips could not be included in the regression, but reduced yield by 1282 and 2321 kg ha^{-1} (16 and 33%) in 2019 and 2020, compared to the same rate applied as biochar. This additional loss indicates that wood chips may greatly reduce yield and not be a viable alternative to wood biochar. The 5.8 pH (Table 1.3) of the wood chips may have been the cause of the reduced yields, as the more acid-tolerant ryegrass (Lolium L.) was prevalent in these plots.

Wheat protein was also only influenced by the main effect of biochar and not the biochar × year interaction (Table 1.4). No regression model fit protein data across years and biochar rate had minimal impacts on wheat protein; protein for the control plots (109 g kg^{-1}) was the statistically equivalent to the protein of the 2, 12, and 73 Mg ha^{-1} biochar rates. These protein levels among treatments were all below the 110 g kg^{-1} threshold and would not have influenced soft white wheat selling price. The interaction of biochar rate × year was only significant for wheat test weight. Wheat test weight was equivalent across all biochar rates in 2019 and averaged 84.7 kg hl^{-1}. At current market prices, soft white wheat test weights below 77.2 kg hl^{-1} incur a price reduction (‘discount’) at \$0.0007 kg^{-1} for each 0.23 kg hl^{-1} between 77.2 and 74.7 kg hl^{-1}, and discounts of \$0.0015 kg^{-1} for each 0.23 kg hl^{-1} below 74.7 kg hl^{-1} (personal communication, Scoular Grain, Ogden, UT). Thus, no discounts would have been applied this year. Test weight averaged 75.4 Kg ha^{-1} in 2020 with no differences among the treatments, except for the wood chip treatment, which measured 70.8 kg hl^{-1}, (6% decrease from untreated plots). Thus, only wood chips decreased test weight and would have been discounted \$0.03 Kg^{-1}, whereas the other treatments would have only been discounted \$0.005 Kg^{-1}.

Soil water tension was only measured during the 2019 growing season due to logistical and equipment constraints in 2020. Soil water tension values for field capacity and maximum allowable depletion (50%) are dependent on soil type and were estimated to be at 10 and 30 kPa at this site. During the 2019 growing season, differences in soil water tension only occurred in the top 30 cm in Cornish (Fig. 3). In general, all treatments with measurements had excellent soil moisture conditions as soil water tension remained below 30 for nearly all the season. The wood chip treatment had the lowest soil water tension, or most available water throughout much of the season. The decreased yield may be the cause for this, as there would have been less crop transpiration withdrawing moisture from the soil. Another interesting observation was how the 22 and 67 Mg ha^{-1} treatments began the season with the same or slightly lower soil water tension than the other biochar treatments, but in mid-July this switched and they began to be the treatments with higher tension, especially the 22 Mg ha^{-1} treatment, which ended the season 15 to 20 kPa higher than the other treatments. Fall moisture is important in semi-arid regions such as Utah, where it can be critical to the next crop, which is often fall planted and can be after irrigation has ceased. In this loamy fine-sand soil, the water holding capacity is small and the soil drains quickly. The size and rate of biochar has effects on bulk density and the water holding capacity of soil (Verheijen et al., 2019). One reason for the increased soil water tension in some biochar treatments could be that the large biochar (19mm) was reducing bulk density enough to increase deep percolation.

1.3.1.2 | Silage Corn

At Mosida, in central Utah, total growing season precipitation was 45, 8, and 100% lower (2018-2020) than the 30-year average of 158.5 mm (Fig. 1.6). GDD units were 2884, 2434, and 4616 (2018-2020), 7, -10, and 71% different from the 30-year average of 2693 GDD. (Fig. 1.5) In this silty loam soil, the main effect of biochar rate or its interaction with year did not influence corn yield or any of the silage corn quality parameters (Table 1.4). The main effect of year influenced all yield and quality parameters. Corn silage yield was 44.4, 40.8, and 35.4 Mg ha^{-1} in 2018, 2019, and 2020, respectively. The declining yields may be largely due to the weather, as 2019 had late planting due to a wet spring, and 2020 harvest was early due to early September frost events. All silage corn quality parameters changed from 2018 to 2019 as follows, protein (9 to 8), NDF (64.60 to 49.16), NDFD (75.28 to 82.68), starch (4.31 to 19.00), and TDN (60.58 to 68.29). The increased NDFD, Starch, and TDN values may be explained by the corn grain measurements in comparison to the full plant measurements, as when only comparing grain, there was no statistical difference from 2018 to 2019, yet overall silage yield was significantly reduced in 2019. Thus, similar to some other studies in corn (Aller et al., 2018; Novak et al., 2019;), wood biochar had no impact on corn production in the first two years after application.

In 2018 and 2019 similar soil water tension trends between treatments occurred in the top 30 cm of soil (Fig. 4). The 0, 11, and 34 Mg ha^{-1} biochar rates began the season equally, but in early to mid-July, the soil moisture tension levels separated, and soil tension decreased for the increasing levels of biochar. This indicated that biochar consistently improved available soil water at this site because crop yield (water demand) did not differ among biochar treatments. However, the enhanced available soil water had no measurable benefit to corn yield or quality.

1.3.2 | Irrigation Level Trials

1.3.2.1 | Silage Corn

Growing season precipitation and GDD measurements in Elberta were the same as in Mosida. Annual precipitation was below the 30-year average (158.5 mm) by 45, 8, and 100% (2018-2020) (Fig. 1.6), and GDD measurements were 7, 10, and 71% different from the 30-year average (2693 GDD) (Fig. 1.5). Silage corn yield responded to biochar in the full irrigation treatment, but not the partial irrigation treatment where water was more limited (Table 1.4). The most notable difference occurred in yield, where the biochar × year interaction was significant. In the dry year of 2018 with full irrigation, biochar applied at 22 Mg ha^{-1} increased silage corn yield from 64.2 to 72.0 Mg ha^{-1}, an increase of 12%. However, the opposite occurred the following year where biochar decreased yield from 61.8 to 55.9 Mg ha^{-1}, or a loss of about 10%. Late planting due to a wet spring in 2019 could be a reason for the yield difference between years. Most silage corn quality parameters were influenced by the main effect of biochar in the full irrigation treatment (Table 1.4). Across both years, biochar raised NDF (43 to 46) by 6%. For NDFD, biochar decreased the value by 2%, from 84 down to 83. Starch was reduced from 297 to 268 g kg^{-1} (11%) and TDN from 710 to 697 g kg^{-1} (2%) when biochar was applied. Of all silage corn parameters measured, yield, starch, and TDN are generally of most concern to growers. There was nothing conclusive on the impact of biochar on yield from this site, other than biochar provided no consistent yield enhancements or reductions and provided no enhancements in a water-stressed environment. However, biochar did cause consistent reductions in silage corn forage quality. These results were similar to those at Mosida and Cornish where biochar provided few to no short-term benefits to crop production in Utah.

The 2018 soil water tension readings at 30 cm showed few differences between the biochar treated and untreated plots within each irrigation treatment (Fig. 1.10). The only notable difference at this depth was that after the final irrigation on 18 September, the plots with biochar did not dry as quickly as the untreated plots under full irrigation. At the 60 cm depth, biochar often slightly decreased water tension, however no corn water stress was visual in any treatment. In 2019, the partial irrigation treatment often had lower water tension with biochar, at the 30 cm depth. This differed in the full irrigation treatment, where there was usually higher water tension with biochar. In silt loam soils biochar can decrease aggregate stability (Aston, Street-Perrottm, Doerr, 2014). The differences observed between the effectiveness of biochar at the partial and full irrigation rate could be due to the duration of wetting with the MESA system being longer than that of the LEPA system used in the partial treatment. If a decrease in aggregate stability is a true cause, initial wetting would have a sealing effect on the soil surface and limit the forthcoming irrigation. In such a scenario, a longer wetting duration could be prone to losing a greater portion of irrigation to runoff.

1.3.2.2 | Alfalfa

In southern Utah at the Cedar City site, growing season precipitation was 42, 10, and 100% below the 30-year average of 100 mm (Fig. 1.2). GDD were 4130, 3598, and 4015 (2018-2020), 12, -3, and 9% different than the 30-year average of 3692 GDD (Fig. 1.1). At this site, where biochar was top-dressed onto a three-year-old alfalfa stand, there was no influence on alfalfa yield in 2018-2020 (Table 1.4) from biochar. The interaction of biochar × year only influenced RFQ in the full irrigation treatment. In 2018, biochar reduced alfalfa RFQ from 361 to 323 in the full irrigation treatment. Although this represents an 11% reduction of an important parameter for valuing alfalfa in the marketplace, it was still within the range requirements to be rated in the most valuable category as supreme alfalfa (USDA, 2020). The 2019 RFQ values were statistically the same with and without biochar, averaging 313. The main effect of biochar influenced RFQ in partial irrigation (Table 1.4), and across years biochar decreased alfalfa RFQ by 22, from 331 (7%). Reductions in RFQ due to biochar could be due to some of the biochar being lifted from the soil surface and into the alfalfa windrow during raking. Another possible cause for reduced RFQ could be from less N uptake by alfalfa, less leaf retention, and lower leaf to stem ratios because biochar is known to have high N adsorption potential (Huang, Fu, Li et al., 2019). The only other place where the main effect of biochar was significant was for NDFD in partial irrigation. In 2018, biochar increased NDFD values from 11.8 to 12.3 (4%). The most important difference between the full and partial irrigation rates was the yield decrease of 15, 18, and 27% (2018-2020) that accompanied the partial irrigation rate. Within each irrigation treatment there were no yield differences with biochar, signifying that biochar may not be helpful for mitigating crop stress in water-limited scenarios. These results support what was observed in the other test crops, that biochar may not have an influence on crop yield.

In 2018 when the biochar was top-dressed onto the field, the partial irrigation treatment often had higher soil water tension with biochar, at both the 30 (Fig. 1.10) and 60 cm depths (data not shown). The full irrigation treatment did not have many differences between biochar and untreated plots at either depth. The 2019 results displayed differences only in the top 30 cm, where the partial irrigation rate had lower soil water tension (more available water) with biochar, while biochar increased the soil water tension in the full irrigation treatment. These results were similar to the Elberta site, where during the wet year of 2019, plots in the full irrigation treatment that were treated with biochar had less plant available water than plots without biochar. There were not significant yield differences that would suggest that the crop was using more water. Soil water tension observations from these trials lack consistent patterns to confidently suggest that biochar would be of benefit or harm to plant available water levels in the soil.

1.4 | CONCLUSIONS

The results at 10 site-years showed no consistent benefit of biochar to yield, crop quality, or soil water tension. Therefore, biochar may not be a feasible tool for conserving water or boosting short-term (2-3 years) production in the major field crops (alfalfa, silage corn, and wheat) of Utah and the greater western U.S. Similar results have been found in neighboring states and in the Midwestern U.S., where biochar treatments have had no impact on yield (Foster, Hansen, Wallenstein, Cotrufo, 2016; Aller, Achontoulis, Zhang et al., 2018). The lack of short-term benefits to crop production or water conservation, coupled with the high cost of producing, purchasing, and applying biochar, indicates that wood biochar is not an economically feasible option for growers without financial incentives or assistance, or massive price reductions. Potential long-term impacts of biochar to soil health enhancement may alleviate these constraints and warrants further investigation in the Western United States where abundant wood feedstocks are available.

TABLE 1.1 Site properties for four trials in Utah from 2018 to 2020, including nearest town, year, GPS coordinates, soil texture, and levels for soil P, K, OM, and pH.

Nearest town	Year	GPS coordinates	Dominant soil texture (classification)	Soil P	Soil K	Soil OM	Soil pH
				mg kg^{-1}		g kg^{-1}	
Cedar City	2018-2020	37.747980, -113.076935	Loam (Fine loamy, mixed (calcareous), mesic Xeric Torrifluvents)	8	56	14	7.3
Cornish	2019-2020	41.991435, -111.955879	Loamy Fine Sand (Sandy, mixed, meis Calcic Haploxerolls)	24	129	15.7	7.1
Elberta	2018-2019	39.897247, -111.955609	Silt Loam (Fine-silty, mixed (calcareous), mesic Xeric Torrifluvents	56	1110	24.8	7.5
Mosida	2018-2020	40.108028, -111.943445	Silt Loam (Finy-silty, mixed (calcareous), mesic Xeric Torriorthents)	23	1483	18	7.8

[a] OM, organic matter.

TABLE 1.2 Location, trial years, irrigation rate, crop, and biochar rates for the two studies.

Nearest town	**Year**	**Irrigation Rates**	Crop (variety) **2018**	**2019**	**2020**	**Biochar Rates**
Cedar City	2018 - 2020	Full, Partial	Alfalfa (Rebound)	Alfalfa (Rebound)	Alfalfa (Rebound)	22.4
Cornish	2019 - 2020	Full	n/a[a]	Soft white wheat (SY Ovation)	Soft white wheat (WB6430)	0,2,6,11,22,34,67,W22[b]
Elberta	2018 - 2019	Full, Partial	Corn (Croplan 4099SS)	Corn (Croplan 4099SS)	n/a	22.4
Mosida	2018 - 2020	Full	Corn (Pioneer 0157)	Corn (Pioneer 0157)	Corn (Pioneer 0157)	0,2,6,11,22,34

[a] n/a, not applicable.
[b]W22, 22 Mg ha^{-1} of wood chips

TABLE 1.3 Biochar and wood chip application method, and P, K, pH, EC, N, C, C:N ratio values measured from a composite sample at each site.

Nearest town	**Type**	**Application**	**P**	**K**	**pH**	**CEC[a]**	**N**	**C**	**C:N ratio**
			mg kg^{-1}			meq 100g^{-1}	g kg^{-1}		
Cedar City	Biochar	Broadcast	34	360	7.5	16.2	6.9	711.9	104
Cornish	Biochar	Incorporated	22	302	6.8	18.8	8.0	717.7	90
Cornish	Wood chips	Incorporated	28	521	5.8	15.8	22.6	468.0	21
Elberta	Biochar	Incorporated	25	334	7.4	11.5	7.3	729.9	100
Mosida	Biochar	Incorporated	22	394	7.2	15.1	6.9	737.1	107

[a]Cation exchange capacity

TABLE 1.4 Significance of *F* tests for the fixed effects of site, biochar rate, and their interaction on yield and quality parameters (CP, crude protein; NDF, neutral detergent fiber; NDFD, neutral detergent fiber digestibility; starch, TDN, total digestible nutrients; RFV, relative field value; RFQ, relative forage quality; and TEST, test weight). Differences were considered statistically significant when $p < 0.05$.

	Irrigation			Crop quality parameters [a]							
Nearest town	Type	Effects	Yield	CP	NDF	NDFD	Starch	TDN	RFV	RFQ	TEST
				---------- $P > F$ ----------							
Cedar City	Full	Y	<0.001	0.009	0.008	0.051	.	0.008	0.015	0.024	.
		Rate (R)	0.479	0.819	0.252	0.271	.	0.845	0.064	0.028	.
		Y × R	0.312	0.573	0.21	0.275	.	0.465	0.107	0.049	.
	Partial	Y	<0.001	0.033	0.373	0.251	.	0.17	0.258	0.277	.
		R	0.067	0.121	0.053	0.039	.	0.208	0.057	0.031	.
		Y × R	0.806	0.200	0.074	0.093	.	0.200	0.084	0.062	.
Elberta	Full	Y	0.015	<0.001	0.133	0.072	0.005	0.018	.	.	.
		R	0.486	0.666	<0.001	0.035	0.004	0.003	.	.	.
		Y × R	0.002	0.449	0.183	0.162	0.621	0.442	.	.	.
	Partial	Y	0.286	0.002	0.142	0.221	<0.001	0.006	.	.	.
		R	0.306	0.285	0.998	0.770	0.334	0.890	.	.	.
		Y × R	0.370	0.391	0.675	0.400	0.682	0.541	.	.	.
Cornish	Full	Y	<0.001	0.133	.	.	.	.	.	.	<0.001
		R	<0.001	0.010	.	.	.	.	.	.	<0.001
		Y × R	0.473	0.841	.	.	.	.	.	.	0.005
Mosida		Y	0.017	0.004	<0.001	<0.001	<0.001	<0.001	.	.	.
		R	0.433	0.914	0.615	0.899	0.127	0.547	.	.	.
		Y × R	0.746	0.735	0.907	0.741	0.050	0.953	.	.	.

[a] CP, crude protein; NDF, neutral detergent fiber; NDFD, n~~a~~eutral detergent fiber digestibility, starch, TDN, total digestible nutrients; RFV, relative feed value; and RFQ, relative forage quality; TEST, test weight.

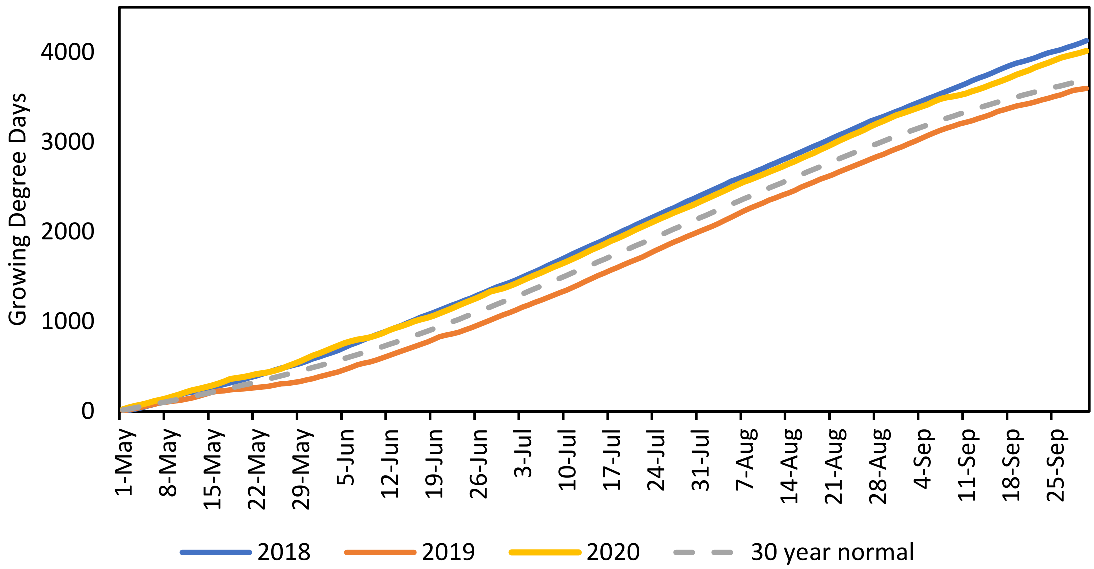

Figure 1.1 Cumulative growing degree days for the Cedar City farm, calculated from daily maximum and minimum air temperatures (adjusted to a base temperature 5°C and a maximum temperature of 30°C) between May 1 to September 30 of 2018 to 2020, shown with the 30 year normal (1981-2010).

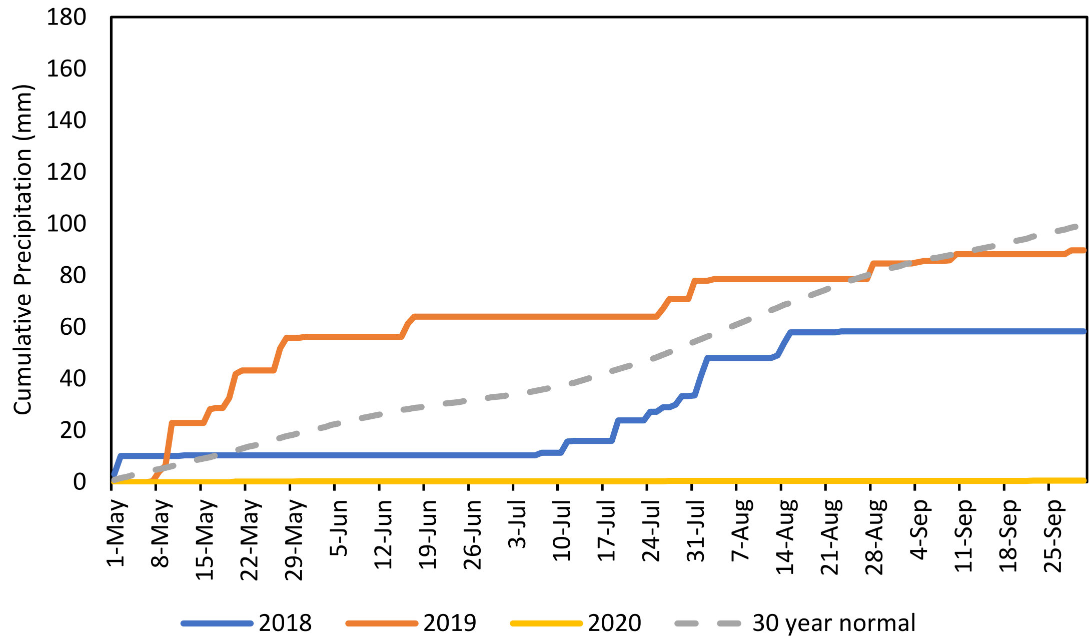

Figure 1.2 Cumulative precipitation measurements for the Cedar City farm measured daily from May 1 to September 30 of 2018 to 2020, shown with the 30 year normal (1981-2010).

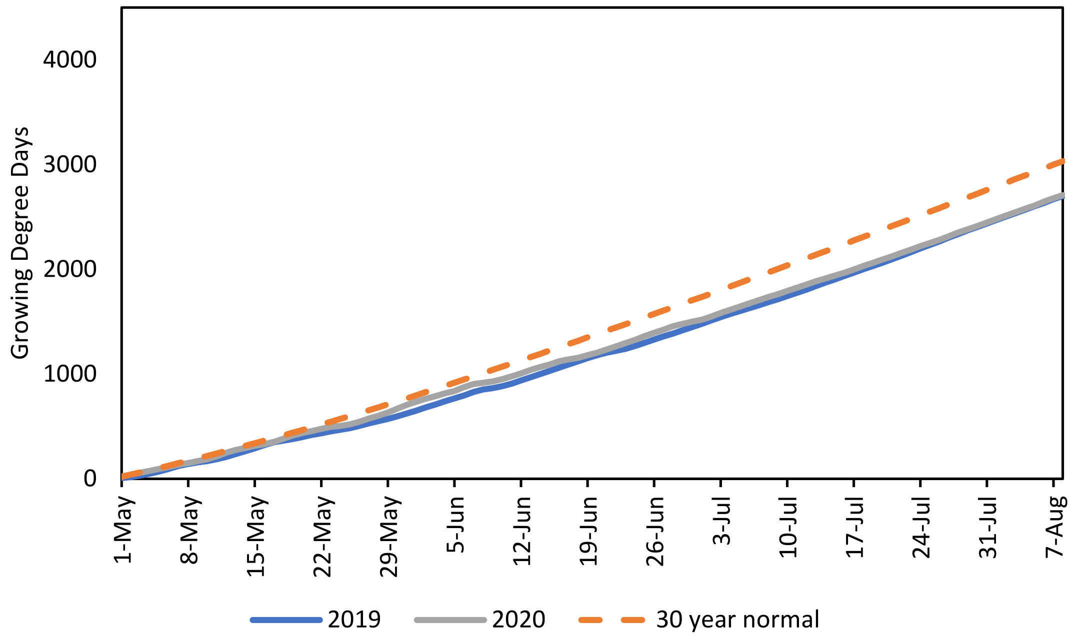

Figure 1.3 Cumulative growing degree days for the Cornish farm, calculated from daily maximum and minimum air temperatures (adjusted to a base temperature 0°C and a maximum temperature of 24°C) between May 1 to September 30 of 2018 to 2020, shown with the 30 year normal (1981-2010).

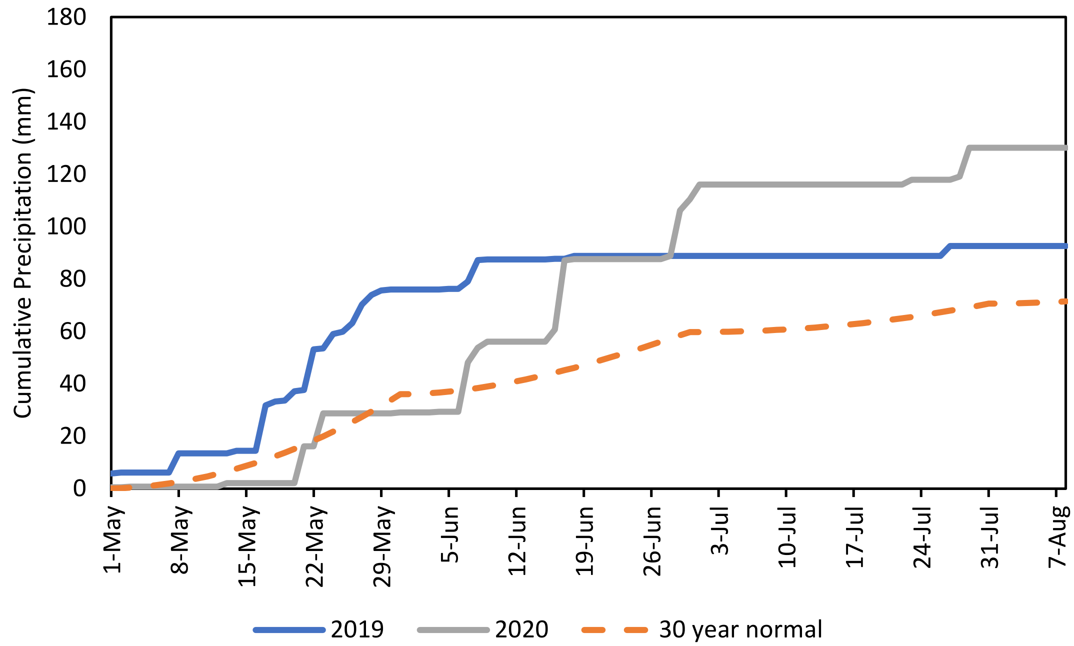

Figure 1.4 Cumulative precipitation measurements for the Cornish farm measured daily from May 1 to September 30 of 2018 to 2020, shown with the 30 year normal (1981-2010).

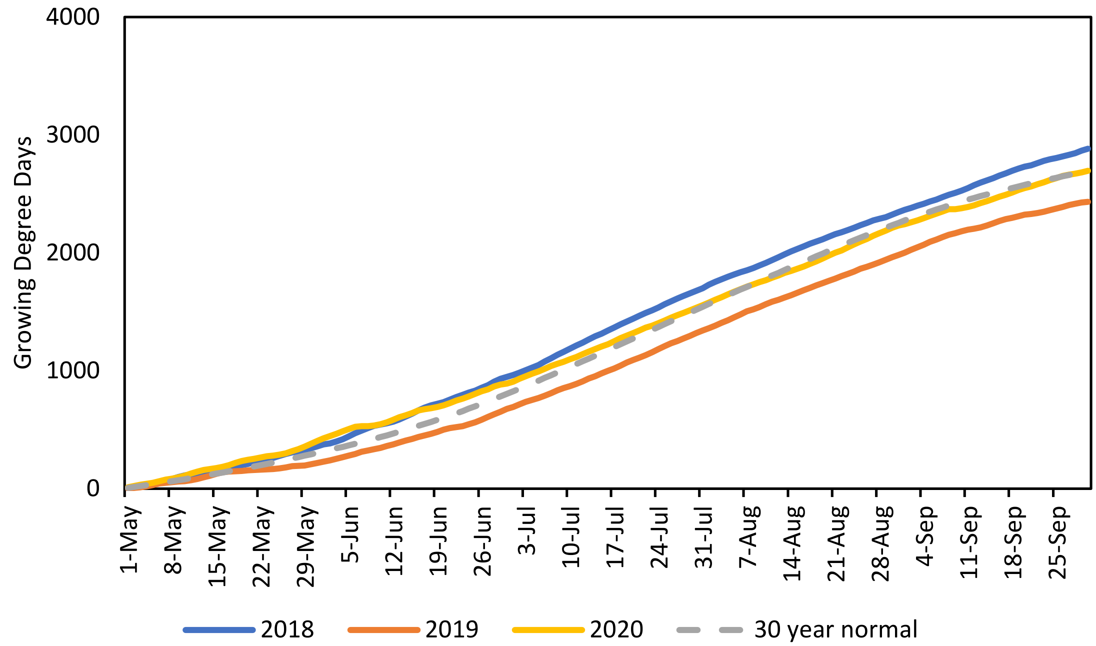

Figure 1.5 Cumulative growing degree days for the Elberta and Mosida farms, calculated from daily maximum and minimum air temperatures (adjusted to a base temperature 10°C and a maximum temperature of 30°C) between May 1 to September 30 of 2018 to 2020, shown with the 30 year normal (1981-2010).

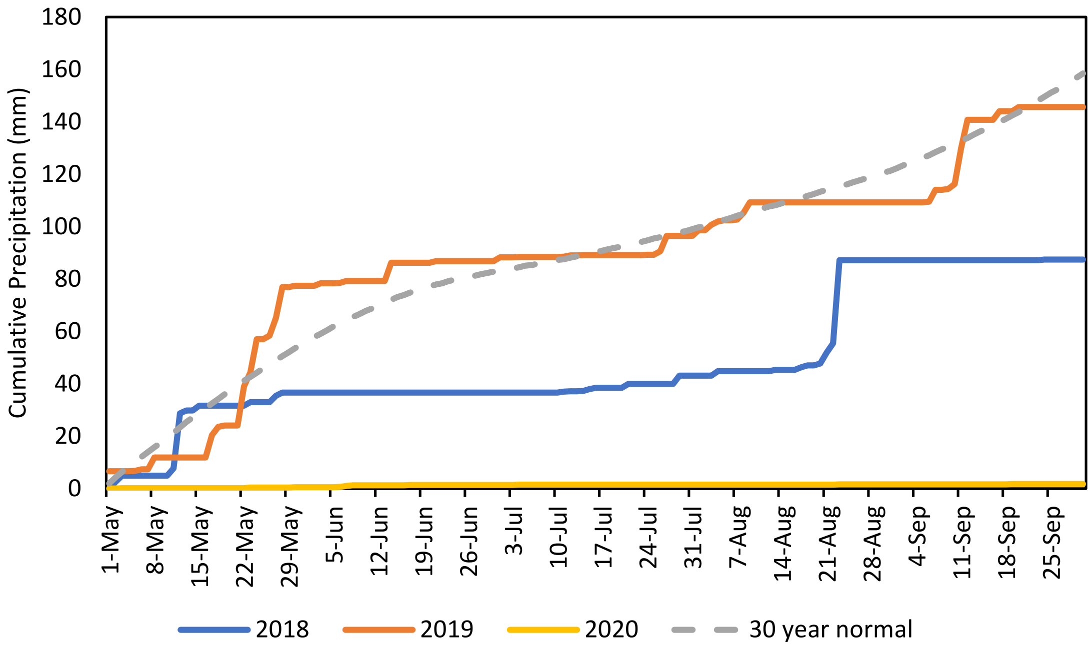

Figure 1.6 Cumulative precipitation measurements for the Elberta and Mosida farms measured daily from May 1 to September 30 of 2018 to 2020, shown with the 30 year normal (1981-2010).

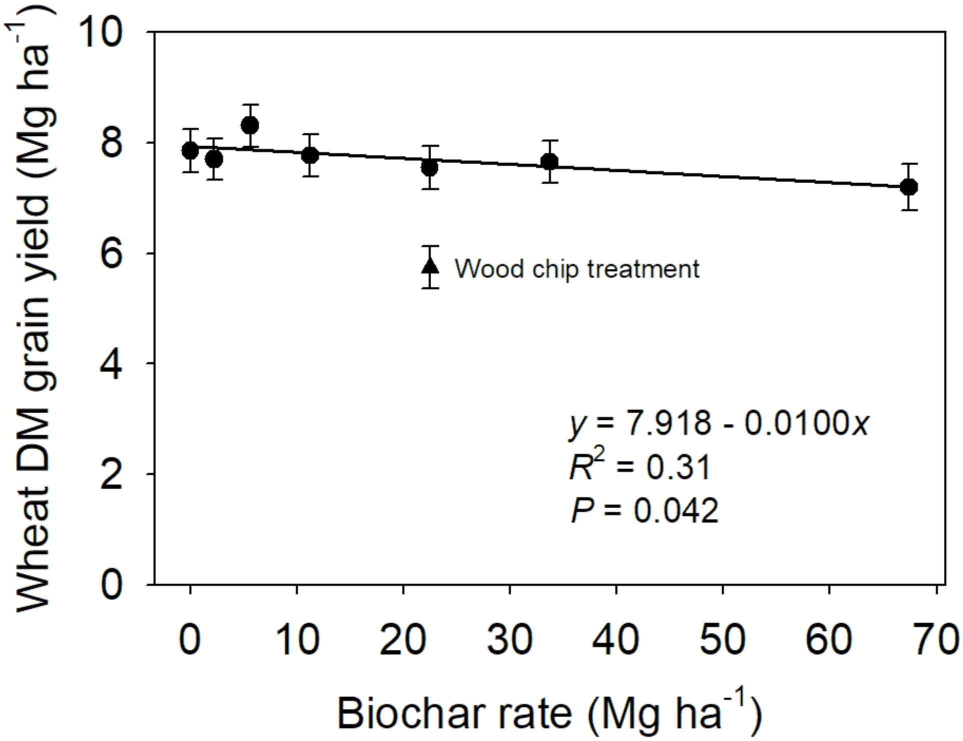

Figure 1.7 Relationship between biochar rate and wheat grain yield at the Cornish site in Northern Utah across 2019 and 2020.

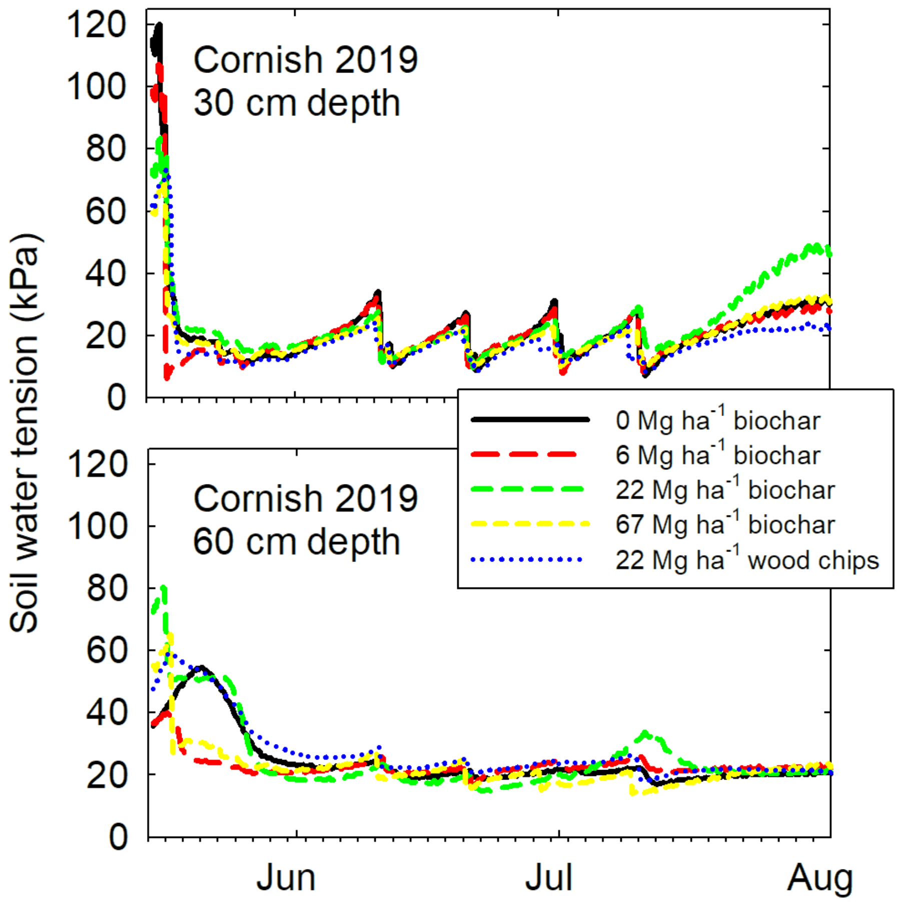

Figure 1.8 Soil water tension to the 30 and 60 cm depth during the wheat growing season in 2019 at Cornish, UT for select biochar rates averaged across three replicates.

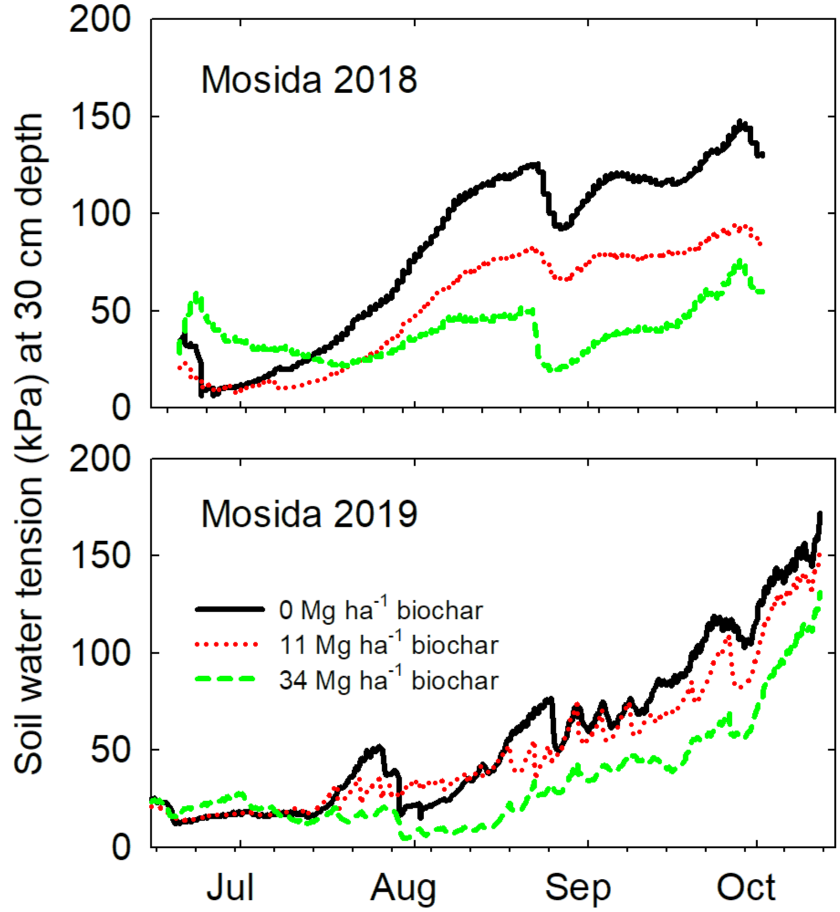

Figure 1.9 Soil water tension to 30 cm depth during the silage corn growing seasons in 2018 and 2019 at Mosida, UT for select biochar rates, averaged across three replicates.

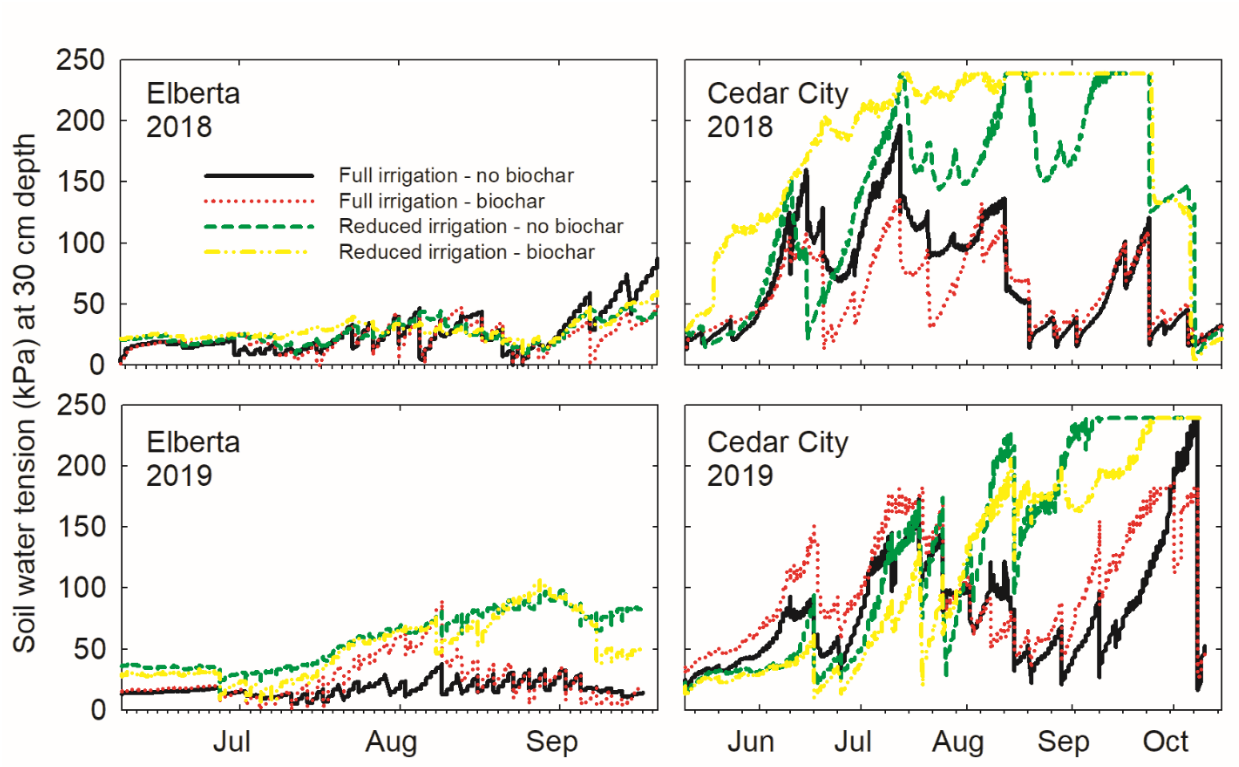

Figure 1.10 Soil water tension to the 30 cm depth averaged across three replicates during the silage corn and alfalfa growing seasons in 2018 and 2019 at Elberta and Cedar City, UT, respectively for full and partial irrigation with and without biochar.

CHAPTER II

GUIDE TO IRRIGATION SPRINKLER PACKAGES FOR PIVOTS AND LATERALS

2.1 | INTRODUCTION

Almost everything in agriculture is becoming high speed, high tech, and high performance. From seed genetics to combine harvesters, the engineering in farming has become extensive and often expensive. In irrigated agriculture, there is a piece of equipment that tacks on more hours than any other piece of machinery on the farm. It drives in circles and never gets fancy green or red paint, but the often-overlooked center pivot plays a vital role in crop health and yield. Pivot technology has continued to surge ahead with the rest of agriculture, but simply having the optimal sprinkler package may be the best investment for this critical piece of machinery.

2.2 | ON-FARM TESTING

Since the beginning of 2018, researchers at Utah State University have been evaluating the performance of several pivot sprinkler packages. This work has been conducted with cooperating farmers and on university-owned farms across the state, to attain data relevant to many soil types and crops (Table 1). At each farm, entire tower-to-tower spans of the irrigation pivot or lateral were outfitted with a designated sprinkler package. Over the course of the growing season, we monitored soil moisture, measured crop yield, and analyzed crop samples for quality.

Research performed at Elberta and Cedar City was a collaborative effort with private farmers and ended in 2020. The Logan and Vernal field trials are part of a long-term water optimization project evaluating sprinkler packages, tillage practices, cover crops, wetting agents, and drought tolerant genetics. In the spring of 2021, research will start in Cedar City at another state-owned farm, with a similar design to Logan and Vernal. Forthcoming results from these studies will be available through the USU Extension Crops team. The following four irrigation systems were evaluated in on-farm testing. Specifications and a cost range of each system are provided for comparison. The costs listed account for clamps, fittings, hose, nozzles, regulators, sprinkler heads, and other supplies specific to each system. Installation labor is not included. Outlet spacing on the pivot is an important cost factor when adopting a design with closer spacing. The efficiencies shown with each system are approximates measured in previous research (Amosson et al., 2011; Oker et al., 2020).

Mid Elevation Sprinkler Application (MESA) 78% efficient

- Most common current system on pivots in northwestern United States
- Rotating parts produce a circular pattern
- Many throw patterns and angles to choose from
- 20 – 75 ft. wetting diameter
- 3 – 6 ft. installation height above the soil surface
- 7.5 – 20 ft. spacing between drops
- $4,500 – $6,000 for a 1300 ft. pivot (125 heads; $38-$50/acre for 120 acres)

Low Energy Precision Application (LEPA) 95% efficient

- Common in water scarce regions of the south
- Bubblers, accelerators, plates, deflectors, and drag socks are available to tailor applications
- 1 – 2 ft. installation height above soil surface
- 2.5 – 3.5 ft. spacing between drops
- $9,000 – $14,000 for a 1300 ft. pivot (325 heads) with first 2 to 3 spans being MESA ($75-$117/acre for 120 acres)

Low Elevation Spray Application (LESA) 88% efficient

- Spray pattern of individual streams
- Pattern angle and coarseness customizable
- 12 – 30 ft. wetting diameter
- 1 – 3.5 ft. installation height above soil surface
- 2.5 – 5 ft. spacing between drops
- $6,000 – $8,000 for a 1300 ft. pivot (250 heads) with the first 2 spans MESA ($50-$67/acre for 120 acres)

Mobile Drip Irrigation (MDI) 97% efficient

- Drip tubing pulled from a pivot-mounted manifold
- MESA heads for germination and chemigation
- Drip tape length is adjusted to set rates
- 1 – 2 gallon per hour emitters every 6 inches
- 1.5 – 3.5 ft. spacing of drip lines

- Automated filter recommended (about $14,000 but can generally service more than one pivot)
- $20,000 – $30,000 for a 1300 ft. pivot ($167-$250/acre for 120 acres with no filter included)

2.3 | RESULTS AND OBSERVATIONS

Results obtained in these studies were variable – no system came out on top as the best choice. We did not determine that any one of these packages could maintain yield at a reduced rate, all the time, in all crops, and in all fields. In fact, sometimes there was no benefit to the advanced systems, yet in other situations they performed just as well as MESA, while applying less water. What we did figure out, was a lot of information that can help guide farmers when making decisions on when and where they might invest in LEPA, LESA, and MDI. Crop selections, water quality, pumping capacity, prevailing winds, topography, and soil type are some of the important field variables that need to be factored into the decision. Another important aspect is the level of potential for water shortages. Installing an advanced system may not always impact yield in a year with normal precipitation. However, if a few seasons of water shortage are expected over the useful life of the sprinkler package, a higher efficiency system may be worth it just for those times.

Below is a review of some of the advantages and disadvantages of each system, based off data, observations, and experiences working with them. Five factors highlighted are maintenance, price, slopes, wheel tracks, and wind. These, and other factors like evaporation or pest control, all come with trade-offs. A small wetting area from closely spaced heads will reduce effects from wind drift and evaporation yet can result in runoff or extra maintenance. Meanwhile a large wetting area will reduce runoff by allowing more time for water infiltration but may incur greater losses to evaporation or poor uniformity due to wind. The intent of this section is to help farmers find the best balance for their situation.

2.3.1 | Mid Elevation Spray Application

This style of sprinkler package was the "control" of the studies; the system that we were comparing the other systems against. It is the least expensive, has the least amount of parts, and like the other systems, operates off low pressure to create large water droplets and reduce pumping requirements. The large wetting area is helpful in tight soils and mildly sloping fields, as longer time is given for irrigation to infiltrate the soil. The trade-offs with having the water spread widely are deep wheels tracks, and losses from wind and evaporation. In Elberta, wind caused a substantial yield drag on the southwest side of most fields. In situations like this, where persistent wind is a factor, MESA packages will usually have more distorted uniformity than the other packages. The 2020 silage corn in Vernal (Table 2) was the only case out of 11 trials that one of the other systems yielded better than MESA at a full rate. This suggests that if water is not a limiting factor for an operation, this is a great choice. Ensuring that the nozzles, sprinklers, and regulators are not worn out is important to maintaining good uniformity, but depending on water quality, most sprinkler components can operate for at least 5000 hours before replacement. We often observed that wheel tracks caused by pivot or lateral tires were usually deeper for MESA than the other three systems because more water is applied to the track. This can cause more wear and tear on the pivot or linear and other machinery operating in the field. For those who have determined MESA is the best system for their application, but are concerned with wheel tracks, the USU Extension Crops team is performing research to improve this problem through simple and inexpensive design modifications.

2.3.2 | Low Energy Precision Application

LEPA was introduced in 1981 (Lyle & Bordovsky, 1981) to combat water limitations and high energy prices. The close spacing, low sprinkler height, and low application pressure of this technology have had an impact on subsequent sprinkler developments. Retrofitting a pivot or lateral with widely spaced outlets is usually done either using simple truss rod clamps to space hoses or by using galvanized pipe, resulting in large prices differences. When tripling the number of sprinkler drops on a pivot for LEPA, the nozzles sizes will be much smaller than MESA packages, which can sometimes lead to more nozzle plugging. Thus, we recommend that the first two to three inner spans of a pivot be equipped with MESA heads and spacing to alleviate this problem and avoid purchasing an expensive filtration system.

A benefit and detriment to these packages is the concentration of water in a small area. Being near the soil surface and wetting only a small diameter decreases the opportunity for water to be lost to evaporation or spread nonuniformly by the wind

(Peters et al., 2019). The precision application also keeps the pivot and wheel tracks mostly dry, reducing the wear and tear on the pivot and other machinery. The downside to concentrating the water in such a small area, is the potential to exceed the infiltration rate of the soil and produce runoff or surface movement (Peters et al., 2019). Due to the potential for this to occur with a LEPA package, they are not recommended for fields with slopes greater than 1% (Senninger Irrigation, 2018).

In all crops at the Logan and Vernal farms where a lateral was used, LEPA maintained yield when applying about 20% less irrigation than the MESA. Both fields have loamy soils that can store a good amount of water. In Cedar City, LEPA performed poorly at full or reduced rates. Alfalfa yield at this field was between 10 to 28% less with LEPA in the second and third year of the trial but was equivalent between MESA and LEPA in the first year (Table 2). This suggested that the negative impact of LEPA was growing with time. There was no clear reason why LEPA performed poorly at this field. One reason could be due to the placement of LEPA on this pivot. It was installed on the last span where uniformity can be more difficult to maintain, as the application rate per nozzle is nearly double that of the LEPA spans on the laterals, increasing the opportunity for ponding and surface movement. During irrigations, it was common to see ponded water in the LEPA. These observations have led us to speculate that the yield drag was due to saturating the top foot of soil. This is something to be aware of when adopting LEPA, particularly near the end of the pivot where the application rate is highest. Optimal results for LEPA may require running the pivot faster than typical MESA applications to apply a smaller amount of water that will avoid ponding and runoff.

2.3.3 | Low Elevation Spray Application

LESA sprinkler packages are a low risk, easy retrofit, that also aims to decrease losses caused by evaporation and wind drift (Neibling, 2015; Swanson & Fipps, 2011). They do not eliminate these problems to the extent that LEPA or MDI can, but the risks are not as great either (Peters et al., 2019). Though intended to be near the ground, these heads have a large effective height range that can be tailored to work in fields with moderate slopes. Many similarities exist between LESA and LEPA, but there are some differences in how they perform, primarily in application patterns. LESA heads spray a large, flat circle of individual streams, and attempt uniformity through close overlapping spray patterns. The diameter covered by each head depends on nozzle, plate, height, and pressure, but is usually between 12 to 30 feet. This results in less ponding and runoff than a LEPA system, yet it still is usually not an ideal system for sloping fields. One negative effect of the overlapping spray pattern is that it will get the wheel track wet and can produce deep wheel tracks like MESA.

In most of the situations where it was tested, LESA yielded just as good, or better than MESA at full or a reduced rate, except in Logan, where it decreased silage corn yield by about 15% two years in a row. We are unsure of what caused the reduced yield, but it can serve as an example of the importance of selecting the right system, and the wisdom of experimenting with only a span of a pivot, if the decision is not clear-cut enough to make you comfortable changing the entire system.

2.3.4 | Mobile Drip Irrigation

This technology has been around for several years, but there have been several improvements and new products on the market in the last five years. For pivots without close spaced outlets, a horizontal manifold is attached to the pivot. This manifold can be fixed at a height specific for a crop, or an adjustable manifold is now available. Vertical, rigid drops come down from the manifold and can have a spray nozzle attached on the bottom for crop germination, chemigation, and fertigation purposes. A flexible length of hose is used to connect the manifold and drip tubing. Every six inches along the tubing are emitters, with water metering diaphragms. To prevent plugged emitters, careful filtration (minimum 80 mesh) is a necessity for these systems. Physical and biological contaminants such as sand, rust, algae, or bacteria can affect emitter performance. A water test is imperative before investing in a filtration system (for more details see "Mobile Drip Irrigation for Pivots and Laterals" Yost et al, 2019). There is a component of added labor to be expected with the use of MDI as well. The drip lines need to be moved out of the way for field operations and should be protected from grazing livestock. Wildlife will occasionally test the durability of the drip lines, but these repairs are usually quick and inexpensive.

MDI may be the easiest system to rank. It is expensive, requires the most labor of any system, and has the most parts to maintain. However, it has shown some significant benefits (Molaei et al., 2020). Our research has produced mixed results and many observations to help farmers know if this is something they want to commit to. In 2018, a design flaw with the drip tubing reduced the output of the emitters significantly in Elberta and Cedar City. At these two sites, irrigation rates with MDI were 40-70% less than MESA instead of our desired 20% reduction (Table 2). Despite drastically lower rates in MDI, it only decreased alfalfa yield by 24%. In the silage corn at Elberta in 2018, MDI yielded similarly to all the other systems with about 40% less water. We made corrections to the MDI for the 2019 growing season, that brought the output rates up to a similar range as the other systems. That year it performed similar to MESA while applying 15% less irrigation, but would not sustain yield at a 30% reduced rate. This indicated an inconsistent ability of MDI to maintain yield with less applied water than MESA. Alfalfa, silage corn, and small grain forage yields for 2020 have shown reduced yields under all levels of MDI, at all three fields where it was tested. In alfalfa, teff, and small grains, it was common to observe crop stunting in the area between the drip tubes. With soil moisture sensors and soil probes, we found that irrigation water would move laterally between the drip lines, but usually occurred about a foot deep, which may have been causing the crop stress. Wheel tracks are generally not a concern with MDI because no water is applied to the track, making MDI an excellent choice for improving track management. Areas where these systems may excel are in high value specialty crops, places with severe water restrictions, crops with large spacing, fields with steep slopes, or on a pivot with a dwindling well capacity.

2.4 | SUMMARY

Research on 11 trials over three years has demonstrated that LEPA, LESA, and MDI can sometimes, but not always, maintain crop yield with about 20% less water than MESA. Thus, one system is not ideal for all scenarios and each field should be carefully assessed to determine which technology might be ideal for the good years and the bad. Compared to upgrading tractors or other farm equipment, it is relatively inexpensive to make changes to the sprinkler package of a center pivot. Determining which system is best for a particular field or application can be complex and often requires some on-farm experimentation. Testing a new sprinkler package on a single span of a pivot may be a smart way to see if a change will be effective for a field, and is a task easily carried out with a little math and some basic tools. Evaluations of investment (about $58, $96, $208/acre for LESA, LEPA, and MDI, respectively) in new sprinkler packages compared to MESA ($44/acre) should include: i) price difference (equipment and labor) between advanced and traditional packages; ii) crop value change from advanced systems (increased or decreased yield and/or crop quality); and iii) changes to water productivity (e.g., greater infiltration, less losses through runoff, drift, and evaporation). These assessments should be factored over the lifespan of a package (see manufacturer recommendations) and account for any anticipated water shortages. If more than the cost of the upgrade ($14 - $164/acre, based on the cost of the various systems above) can be recovered over the lifespan of the package, then advanced systems should be utilized.

Table 2.1 Data for On-Farm Trials Conducted Across Utah From 2018 to 2020.

Nearest town	**Years**	**Dominant soil texture**	**Water storage per foot of soil**	**Slope**
			inches	%
Logan	2019–2020	Loam	2.2	0 – 3
Elberta	2018–2019	Silt loam	2.1	1 – 2
Vernal	2020	Clay loam	2.0	0 – 2
Cedar City	2018–2020	Sandy loam	1.7	0 – 2

Table 2.2 Yield Differences of Various Irrigation Systems Shown as % Difference from MESA Yield for On-Farm Trials in Cedar City and Elberta, Utah.

Irrigation System	Cedar City				Elberta	
	2018 Alfalfa	2019 Alfalfa	2020 Alfalfa		2018 Silage corn	2019 Silage corn
MESA (tons/acre)	**4.0**	**6.4**	**4.9**		**27.2**	**23.5**
LEPA	0	-10%	-28%		0	0
LEPA reduced 20%	-12%	-18%	-22%		0	-13%
LESA	.	.	.		0	0
LESA reduced 20%	.	.	.		.	0
MDI [a]	-13%	-9%	-11%		.	0
MDI reduced 30%	-24%	-22%	-35%		0	-13%
Full rate applied (inches)[b]	26.4	23.5	26.6		30.2	30.8

Note. Average of four yield measurements per treatment. Only statistically significant differences at a confidence level of 95% are shown. “0” denotes there was no difference in yield from MESA. Percent reductions are as designed and may vary from the actual output.

[a]At Cedar City in 2018, the “MDI” applied 40% less than designed and “MDI reduced 30%” was actually reduced by 60%.

[b]Full rate application measured in MESA.

Table 2.3 Yield Differences of Various Irrigation Systems Shown as % Difference from MESA Yield for Water Optimization Trials in Logan and Vernal, Utah.

Irrigation System	Logan				Vernal		
	2019 Silage corn	2020 Silage corn	2020 Alfalfa		2020 Silage corn	2020 Small grain forage	2020 Teff
MESA (tons/acre)	**26.2**	**39.8**	**3.1**		**33.8**	**2.9**	**2.9**
LEPA	0	-10%	0		+13%	0	0
LEPA reduced 25%	0	0	0		0	0	0
LESA	0	-16%	0		+10%	0	0
LESA reduced 25%	-14%	0	0		+10%	0	0
MDI	0	-13%	0		-26%	-44%	-77%
MDI reduced 25%	0	.	-41%		-30%	0	-80%
Full rate applied (inches)[a]	13	13	13.8		27.2	14.7	12.3

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